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OMEGA CHART BASE SELECTION FOR DIFFERENTIAL AND STANDARD USE.(U)

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ER Swanson

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ADMINISTRATIVE INFORMATION

The accomplishment of this work was originally incidental to obtaining charts for the Differential Omega evaluation held in the Gulf of Mexico in spring 1977. The substance of the material was documented in a memorandum to file of 21 July 1976. Subsequent events have indicated that although the material is straightforward technically, it is of sufficient operational importance to warrant formal publication. The material was expanded and formatted as a report in November 1977. Work was accomplished for the Naval Electronic Systems Command under ELEX PO 4-4521 (NOSC A111).

A draft of this report was circulated at the second meeting of the Intersessional Working Group (ISWG) on Differential Omega of the Intergovernmental Marine Consultative Organization (IMCO) in Paris 3–7 April 1978 and was discussed at the meeting. The submittal designation of the draft report was ISWG-DO-II/12 and was dated 29 March 1978.

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Discusses the relationship between Omega errors and the choice of chart base and reviews the present choice. The error budget for Differential Omega is noted and the portion related to chart base identified. Optimum chart bases would be c/v=0.99691 during the day and c/v=0.99973 at night for a frequency of 10.2 kHz in the temperate latitudes. The best single velocity choice is c/v=0.9985. A chart base of c/v=0.9985 is recommended for Differential Omega at a frequency of 10.2 kHz.

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PROBLEM

Select an appropriate chart base for Differential Omega.

RESULTS

1. The relationship between Omega errors and the choice of chart base is discussed together with an historical review of the present choice of chart base.

2. The error budget for Differential Omega is noted and the portion related to chart base identified.

3. Optimum chart bases would be c/v = 0.99691 during the day and c/v = 0.99973 at night for a frequency of 10.2 kHz in the temperate latitudes.

4. The best single velocity choice is c/v = 0.9985.

RECOMMENDATIONS

1. A chart base of c/v = 0.9985 is recommended for Differential Omega at a frequency of 10.2 kHz.

2. Serious consideration should be given to changing the chart base of standard Omega to match the Differential Omega chart base.

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INTRODUCTION

If Omega signals propagated with a velocity which was universally constant, there would be little problem in selecting a velocity for charting. In practice, however, Omega velocities are neither spatially nor temporally constant. Thus, selection of an appropriate charting velocity or velocities entails numerous considerations and compromises.

Velocity difference yields "dispersion" error interpolation error

Selection of a charting velocity different from the instantaneous propagation velocity introduces a "dispersion" error which is essentially an interpolation error. It is not envisioned that standard Omega navigators will perform elaborate interpolation of propagation corrections to obtain those for their precise location. Rather, it is assumed that the corrections are generally applicable over a region of some size, viz: a 4 X 4 degree grid. It is the chart base which determines the effective velocity assumed during the extrapolation of propagation corrections from their location of precise applicability to that of use.

Charts: for conventional manual fix reduction

Automatic receivers: no reduction errors for standard Omega

Consideration of chart base tacitly assumes construction of special charts on which the hyperbolic lines-of-position are printed. It is noteworthy that these are used only with the manual or traditional methods of fix reduction. Automatic standard Omega receivers will generally compute the propagation corrections for very nearly the proper time and location of use. In this case, there is little need for interpolation and significant interpolation errors do not arise.*

4 X 4° grid yields 1/2-mile errors

The importance of chart base selection can be illustrated by assuming that a chart base is selected for which the assumed velocity is 0.3% different from that actually prevailing. If corrections are published for a 4 X 4 degree grid, then at the equator one could be a maximum of 2 degrees in both latitude and longitude from the actual point for which the propagation corrections were computed. This corresponds to $2\sqrt{2}$ degrees = 170 nmi, or 21 hyperbolic lanes of 10.2 kHz on the baseline. The assumed 0.3% difference in velocity thus corresponds to 0.06 lane, or 1/2 nmi. That is, the choice of chart base combined with the selected publication density of propagation corrections will lead to an interpolation error of 1/2 nmi in this case. The foregoing example was chosen to approximate the usual difference between actual velocities prevailing at night at 10.2 kHz and those assumed for charting. Indeed, the publication density for propagation correction was originally selected to keep peak night interpolation errors from exceeding about 1/2 nmi.

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*Automatic receivers may internally employ the equivalent of a chart base, but this will tend to have no effect on accuracy once the initial computational iterations are complete and will have nearly negligible effect on convergence time.

The foregoing result is a direct consquence of using propagation corrections at other than their point of computation or measurement. The resultant error will have the character of a radial error oriented along the line joining the user and reference point and proportional to the separation range. Indeed, the magnitude will be equal to the round-trip ranging error which would be obtained from ranging directly on the reference while interpreting separation on the assumption of particular velocity error. This is not unexpected. Radio navigation using time of arrival or phase comparison operates because of differences in these factors from place to place. Positional interpretation requires knowledge of velocity. If an error in velocity is made, one expects the positional error to depend on the net distance or distance difference over which propagation at the improperly assumed velocity occurs. Navigationally sophisticated readers may wish to complicate the physics through consideration of various lines-of-position, crossing angles, and divergences. Projections on various imagined axes are conceivable, but the results will be the same. Situations with unfavorable geometric dilution of precision can be imagined in which fractional lane errors for a fixed separation may be small, but the dilution itself ensures that the corresponding position errors will be similar.

Errors insensitive to LOP geometry

INTERRELATION BETWEEN PROPAGATION CORRECTION AND CHART BASE

Considerations similar:
Standard Omega
Differential Omega

The same type of fundamental interrelationship prevails between propagation corrections and chart base for both standard and Differential Omega. In either case, a propagation correction is established for a particular location which will then be applied at some other location. In standard Omega, the correction is a Predicted Propagation Correction (PPC) computed in advance for the center of a grid square and disseminated by publication. In Differential Omega the propagation correction may be measured at a beacon location and disseminated by telemetry. It is noteworthy that for neither system is the chart base choice a fundamental accuracy limitation in that the resulting errors must necessarily be incurred. It has already been mentioned that more elaborate interpolation techniques could be used to reduce the error on standard Omega. Errors with Differential Omega could be reduced by use of highly interpolated predicted propagation corrections in conjunction with the correlations obtained by telemetry; by use of telemetry corrections received from beacons on both sides of the using location; or by an untried system called Gradient Differential Omega.

Correction Dissemination:
Publication vs telemetry

The practical point is that all these more sophisticated techniques require an increased instrumental or system complexity and/or an increased work load in fix reduction so that it is more practical to perform simple interpolation and absorb the resulting errors into the system design budget.

Figures illustrate: phase variations are not identical

The essential problem can best be understood by considering figure 1. Figure 1A shows a hypothetical phase variation at some location while figure 1B shows similar phase variation at a location perhaps some hundreds of miles from the first location. It is immediately obvious that: (1) the diurnal variations of phase are similar but not identical and (2) the absolute values of the phases are markedly different. The problem is how best to exploit the similarity in the diurnal variation while partitioning the spatial variation out as a simple fundamental variation. The spatial variation is, of course, the primary feature which allows the signal to be used for navigation. Diurnal variation or minor spatial variations due to differences in ground conductivity or other geophysical details are unwanted secondary variations which are to be removed.

Conventional corrections: figure 2

Figure 2 shows the variation of phase from figure 1A taken against a reference value of 242.30, curve A. The reference value serves to define zero on the variation graph and also the chart base insofar as the effective groundwave propagation path length to site A is known. For the circumstances illustrated, assuming a frequency of 10.2 kHz, the chart base would be c/v = 0.9974. Also shown on figure 2 is the diurnal variation from figure 1B. The relative relationship of the curves is approximately as would be expected for a frequency of 10.2 kHz and the conventional chart base of c/v = 0.9974. The line-of-position of site B as illustrated would be about 271.90. Note that the lines-of-position at both site A and site B are determined by the chart base and correspond to zero phase variation.

Alternative choices: figure 3

Alternative choices of chart base are illustrated in figure 3 for a frequency of 10.2 kHz. Figure 3A is identical to figure 2 and illustrates a chart base of c/v = 0.9974, corresponding to propagation at a velocity near that prevailing during the day. Figure 3B illustrates a chart base of c/v = 0.9985, corresponding to propagation at a velocity intermediate to those prevailing during the day and at night. Figure 3C illustrates a groundwave chart base, c/v = 1.0000. The disparity between curves A and B of figure 3 illustrates the error which would be incurred by using the variation of site A at site B as transferred, or "interpolated," using the various chart bases. The disparity in the total magnitudes from figure 1 is a real propagational variation. However, the resulting interpolation errors can be distributed largely at will

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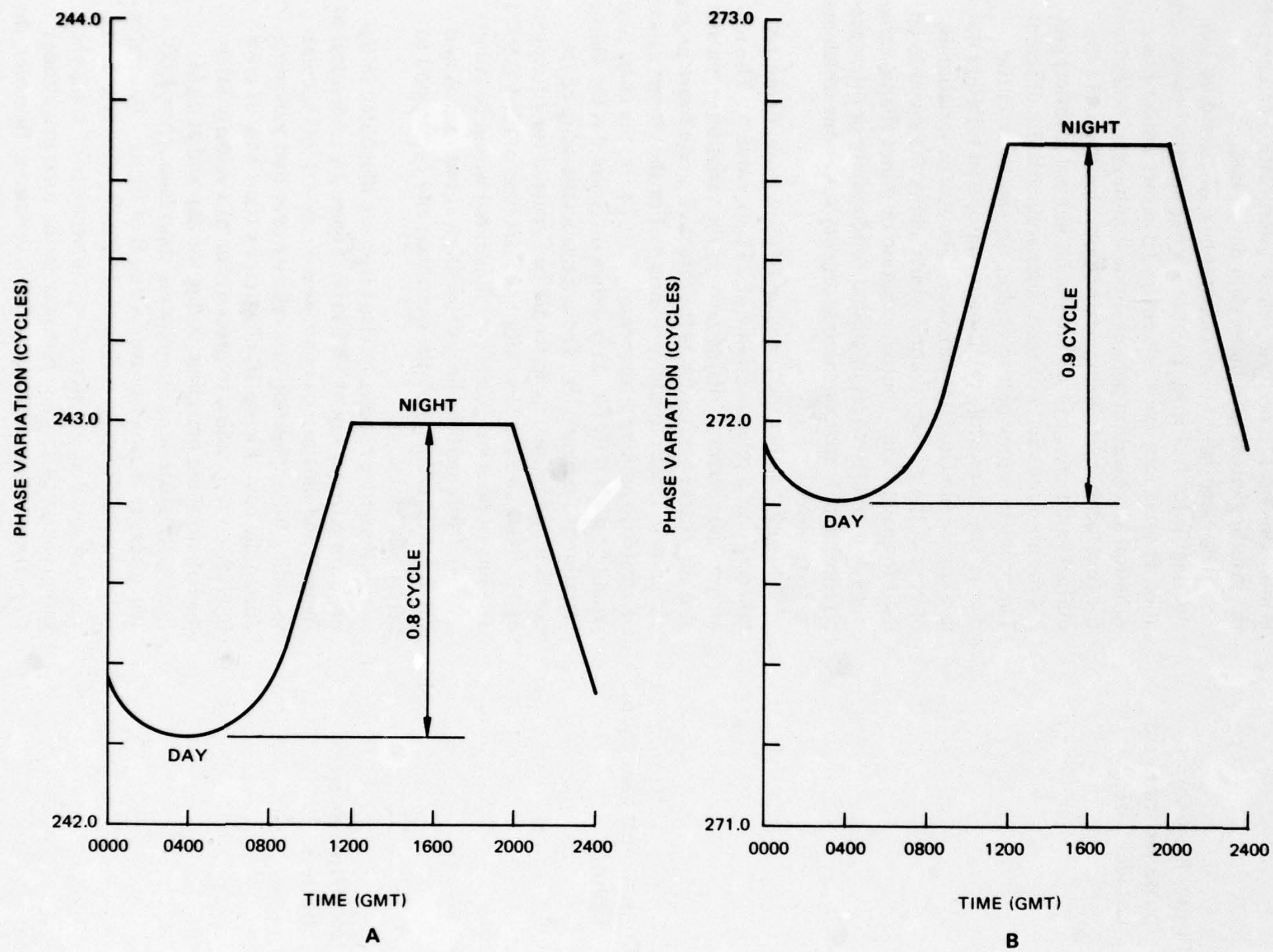

Figure 1. Hypothetical diurnal phase variation at two separated sites A and B.

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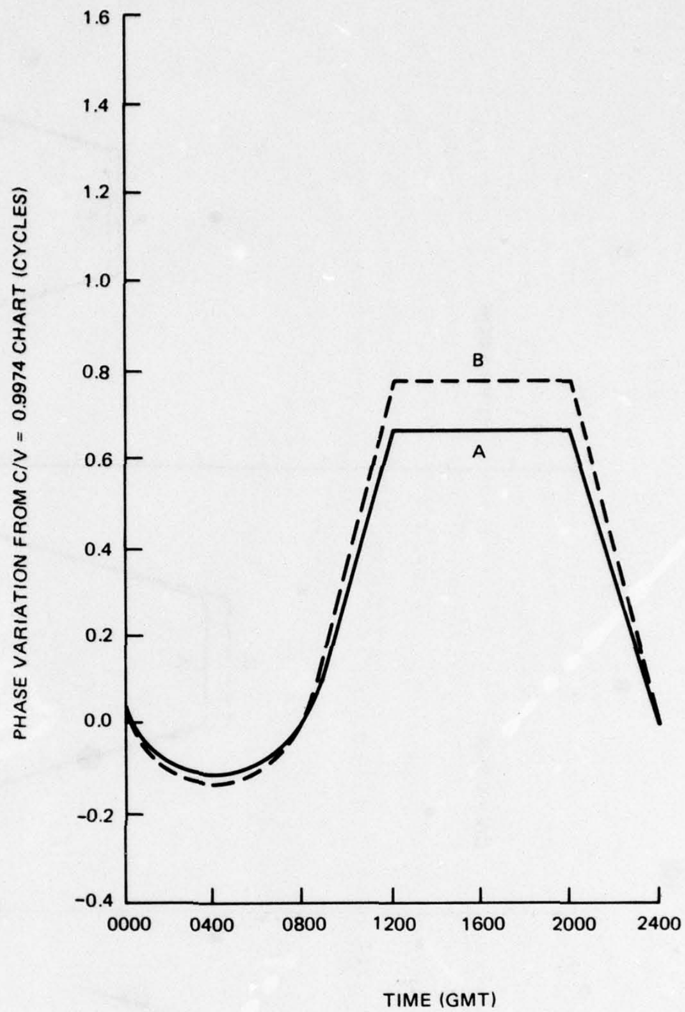

Figure 2. Phase variation from c/v = 0.9974 chart (10.2 kHz).

throughout the 24-hour day by choice of chart base. The error will always be zero when the prevailing velocity corresponds to the chart base. The conventional c/v = 0.9974 chart base tends to minimize errors during the most stable daytime period but as a consequence yields comparatively severe errors at night. The conventional chart base was chosen so as to degrade system accuracy by a nearly constant percentage of system capability. Alternatively, the choice of a groundwave chart base for standard Omega would tend to substantially degrade the daytime capability while providing little degradation to the less stable night period, thus leading to a system of relatively constant accuracy but at the expense of daytime accuracy.

Conventional base: degrades by percent of capability

Groundwave: constant accuracy

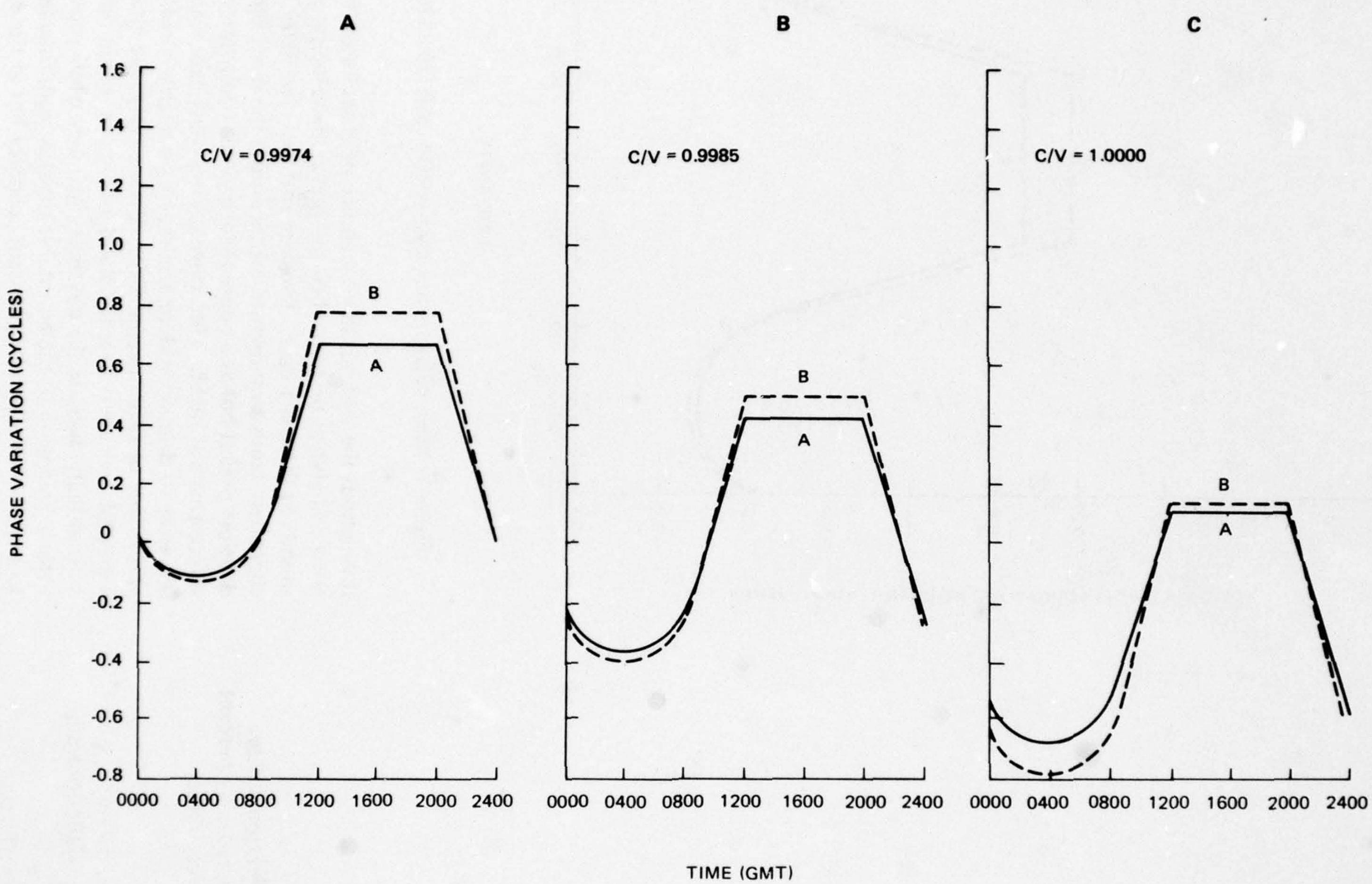

Figure 3. Phase variation using three different chart bases (10.2 kHz).

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Intermediate: truncates maximum error

The intermediate choice chart base, c/v = 0.9985, tends to degrade both day and night accuracy by similar amounts but to limit the typical interpolation errors to the minimum possible value. This is especially appealing for Differential Omega in that the resulting statistical error distribution tends to be truncated at the lowest possible value. It is true, however, that conditions will be such as to produce the comparatively low maximum interpolation errors a relatively large percentage of the time. The choice of chart base thus affects not only the root mean square errors but also the nature of the statistical distribution itself. It is noteworthy that, depending on application, the optimization rationale may vary. For example, for track navigation on the high seas, it may be most desirable to improve economy through optimizing median error, thus providing a means to adhere to an intended track. In the confluence zone it may be more desirable to enhance safety through minimizing large excursions as represented, for example, by the 95th percentile deviations.

Base defines all coordinates

An obvious but major aspect of the choice of chart base is that it serves to define the system or line-of-position coordinates of all points. For example, in the sites previously considered we have (table 1):

Table 1. System coordinates of lines-of-position.

Chart Base	*Location*	
(c/v)	Site A	Site B
0.9974	242.30	271.90
0.9985	242.57	272.20
1.0000	242.93	272.61

That is, any communication between users in system coordinates must be made with a mutual understanding of the chart base – a practical problem in that if Differential Omega corrections are to be offset to the coordinates of the monitoring location, there must be an understanding of chart base so as to define the monitor location coordinates and chart base for users.

The mathematical definitions of chart base and the interrelationship to prevailing velocities and propagational variations are contained in appendix A of reference 1. Fundamental units

1. Navy Electronics Laboratory Report 1305, Omega Lane Resolution, by ER Swanson, 5 August 1965

are defined as well as the nature of the Predicted Propagation Correction (PPC).* One subtlety is an implicit units conversion associated with the propagation correction process. Phase is measured in angular units such as degrees or more commonly cycles or centicycles (cecs, one cec = 0.01 cycle). Navigational lanes are essentially dimensionless distances and are measured in lanes or centilanes (cels, one cel = 0.01 lane).

Units defined:
cec
cel

After considering fundamental definitions, reference 1 proceeds to discuss construction of navigation charts and observes:

> "Drawing one set of lanes for each frequency to be used and then drawing several charts corresponding to various velocities appropriate for propagation at various times of the day, throughout various seasons of the year, would then yield a 'simple' means of converting phase readings into position loci. Unfortunately, the resulting profusion of charts would be intolerable. Instead, a base frequency and base charting velocity may be chosen and then a simple set of lines constructed."

Single chart base:
all times
all frequencies

Even in the retrospective view of the author, the decision to use a universal chart base to be applied at all times of day and at all Omega frequencies was one of the better early decisions in the design of the Omega system. This is not to say that the base selected was necessarily correct or that other bases may not be warranted under special circumstances, only that the decision to implement a simple charting criterion and correspondingly simple interface with the PPCs has weathered the test of time. Mentionable is that the temptation to incorporate various secondary spatial variations such as those associated with ground conductivity into the charts themselves was withstood in the interest of simplicity. The decision to burden the propagation corrections with all spatial and temporal complexity except that associated with spheroidal geometry has been vindicated. The only useful subject for discussion is whether a different chart base should have been selected or whether special applications may warrant consideration of additional chart bases for use in special circumstances. In addition to Differential Omega, special circumstances which might warrant different chart bases are widespread use of Composite Omega or Difference Frequency

Spatial and temporal complexity in PPCs

Special Purpose Charts

*The term "skywave correction" is used in reference 1 to represent Predicted Propagation Correction (PPC). The terms are identical except for sign, which was reversed shortly after publication of reference 1 so as to agree with standard navigational practice. "Phase variation" as shown in figures 2 and 3 is identical to the older "skywave corrections."

Omega. In Difference Frequency Omega the 3.4-kHz difference between 13.6 and 10.2 kHz is used directly for navigation. Although it does not possess the accuracy capability of navigation using the carriers, the ambiguity is only one-third as severe as at 10.2 kHz and, under ordinary circumstances, the effective relative group velocity is $v/c = 0.9914$ both at night and during the normally illuminated day. That is, charts could be constructed which could often be used directly both during the day and at night.*

13.6 kHz PPCs, figure 4

Thus far, the idealized considerations of figures 1 through 3 have been based on a frequency of 10.2 kHz only. As it is expected that the other Omega frequencies would use the same charts scaled only by the frequency ratios, it is pertinent to illustrate phase variations equivalent to those illustrated in figure 3 but for 13.6 kHz. This is done in figure 4, which is based on the observation that the diurnal phase changes in cyclic units are similar at the two frequencies but the nominal group velocity both day and night is $v/c = 0.9914$. For the example previously considered, these facts combine to indicate that the corresponding 13.6-kHz phase measurements at 0400Z would have been 323.89 at site A and 363.46 at site B with similar phase changes, in cyclic units, throughout the 24-hour day. The reference system lines-of-position at the two sites remain as indicated by table 1, since the line-of-position is defined to be at the base frequency of 10.2 kHz. However, multiplication by a factor of precisely 3/4 must be introduced in reducing the 13.6-kHz phase measurement to the charted lane.

13.6-kHz disparities larger

Multifrequency errors:

Standard Omega: negligible

A major feature of figure 4 is the large disparity between curves A and B, especially in figure 4A. That is, the conventional choice of chart base leads to relatively large interpolation errors at 13.6 kHz. This undesirable result was considered in making the original choice of chart base for standard Omega. However, as 10.2 kHz was viewed as the standard frequency for manual navigation, little weight was attached to possible interpolation errors at 13.6 kHz. More complex interpolation procedures can certainly be applied if necessary in very occasional lane resolution problems. In practice, the dominant use of 13.6 kHz is with automatic receivers for which interpolation errors are not significant. Thus, in standard Omega, a strong de-emphasis on 13.6-kHz operation is probably warranted in chart base selection. This may not be entirely true for Differential Omega. The primary frequency for manual

*Note, however, that during transitions the effective velocity is higher than nominal. Also, although the constancy of the velocity holds over a wide range of geophysical conditions, there are major divergencies if propagation is over ground of extremely low conductivity.

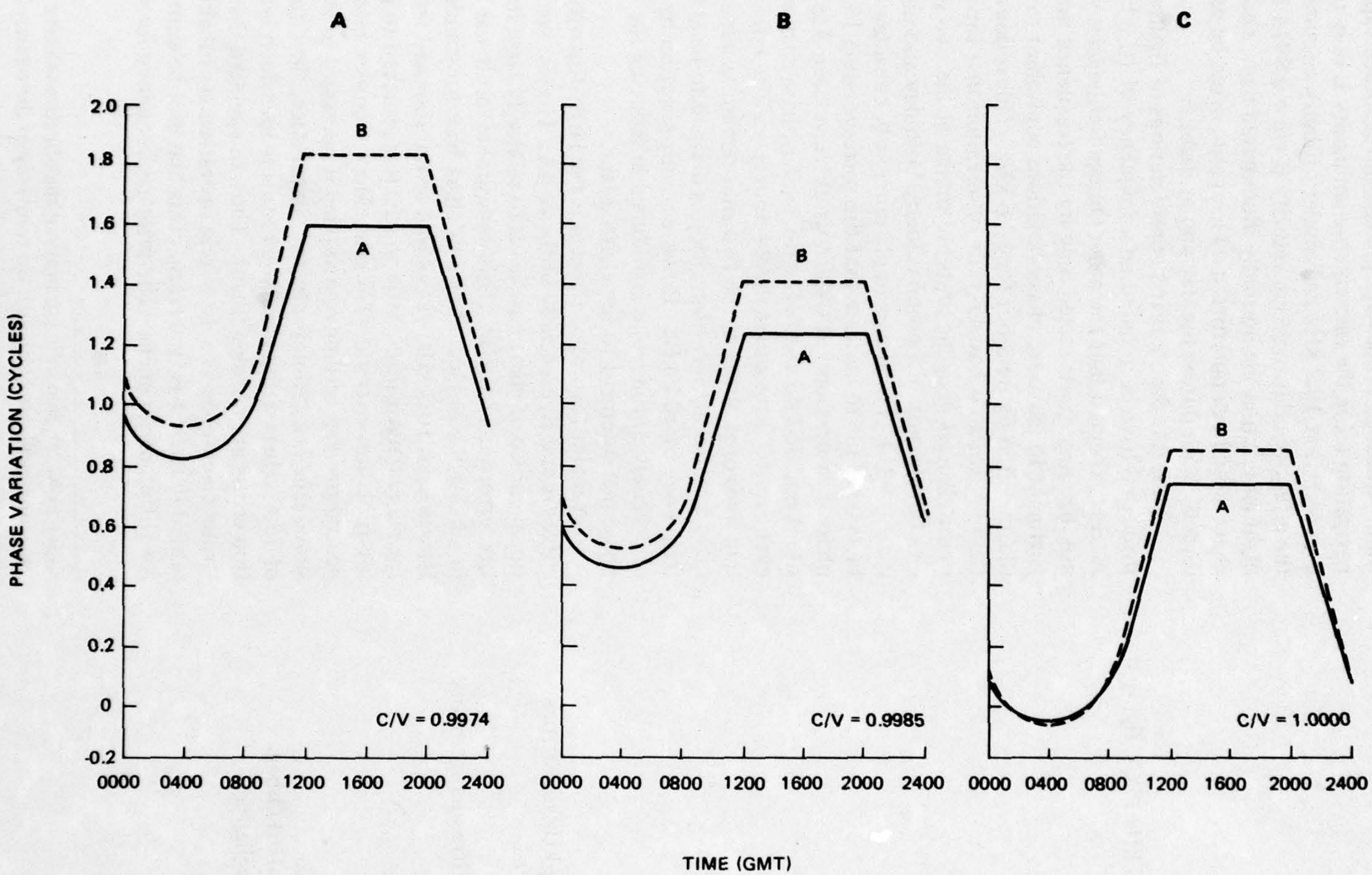

Figure 4. Phase variation at 13.6 kHz using three different chart bases.

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use is envisaged to remain 10.2 kHz, although noise degradation is less at 13.6 kHz and noise degradation is a much larger fraction of the error budget for Differential Omega.

Differential Omega: major concern

The major problem would appear to be possible use of Differential Omega with fully automatic multifrequency receivers. Automatic receivers cannot remove phase variation disparities equivalent to interpolation errors unless they are provided with details of the monitoring beacon location and additional software complexity. As errors introduced through using an optimum chart base form a major or dominant fraction of the Differential Omega error budget at long range, use of a base which is considerably sub-optimum for 13.6 kHz can only introduce large errors. One possibility of considerable merit is to choose the equivalent of a separate chart base or bases to reference corrections for Differential Omega at 13.6 kHz or other Omega frequencies. This would permit simultaneous minimization of errors at all frequencies. All that would be needed would be to supply automatic receivers with software containing the various effective chart bases to be employed; ie, one additional number for each frequency additional to 10.2 kHz. Operation would then be universal without need for specifying locations of individual beacons. Use of effectively multiple chart bases for referencing Differential Omega would not necessarily imply any change in conventional procedures for standard Omega but would introduce additional complexity to anyone trying to use multifrequency Differential Omega manually.

The foregoing pages have developed the major aspects of chart base selection using realistic if hypothetical diurnal variations applicable to two sites, A and B. Before leaving these examples it will be illustrative to elaborate and note some limitations.

LOPs:
Radial
Hyperbolic

First, the diurnal phase variation of figure 1 was drawn as if propagation were over a single path and phase were measured against a properly synchronized reference. The line-of-position in this case is radial rather than the more common hyperbolic line-of-position. In addition to introducing some complexity into the diurnal pattern, use of a phase difference results in the well known "doubling" of phase change per wavelength change on the ground, since a displacement toward one station may be away from the second and the measurements are combined subtractively. That is, the groundwave range displacement between sites A and B of (272.61 – 242.93) = 29.68 cycles corresponds to an increase in range of 471 nmi. If normal hyperbolic operation had been considered, the corresponding displacement to effect the same cyclic variation, and hence the same interpolation errors, would have been only half as much. It may be noted that the hyperbolic lines-of-position are also defined with an arbitrary addition of 900 to the cycle difference count at 10.2 kHz.

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Second, the cyclic variations of figure 1 were drawn as though the sun completed rising over the path about 0000Z; set over the easterly end about 0800Z and the westerly end about 1200Z; while rising over the easterly end about 2000Z. The night near 1600Z is shown as being relatively flat while a slow variation is shown throughout the day centered about path noon at 0400Z. This type of idealized variation can be relatively well approximated for either a hypothetical site A or B but not both. For the transition times to be identical at both sites, the path would have to be oriented north-south and observed at the equinox. If this were true, the transitions would have to be substantially more abrupt. Nonetheless, the illustration is a valid indication of the trend in that transitional disparities between A and B can be viewed as either positive or negative depending on which site is easterly and the path orientation. Thus, interpolation errors during transitions will tend to balance as illustrated with chart base selection. It is, however, notable that higher than nominal phase disparities can occur during transitions due to time disparities, between the reference location and the location of application. These errors may dominate for relatively short periods of time. Although potentially large, such errors are limited by maximum rates of ionospheric change as indicated by ionospheric time constants.[2]

Sunset/sunrise time differences: large transient disparities

CHART BASE FOR DIFFERENTIAL OMEGA

Considerations

The best accuracy can be obtained from Differential Omega by using navigational charts employing realistic charting velocities. The problem is to determine typical conditions so as to minimize the "dispersion" error previously discussed which arises from use of various chart bases. As noted, the "dispersion" error acquired due to differences between actual velocity and that used for the chart base is the most significant single error source for Differential Omega when at nominal ranges such as 100–200 nmi. Considering the importance of bounding the Differential Omega error, it is thus desirable to choose a chart base corresponding to a velocity intermediate between day and night. This will yield a navigational fix with a moderate error during the day, a similar but opposite moderate error at night, but never the full positional error corresponding to the velocity change between day and night.

Dispersion error dominant

2. **Naval Electronics Laboratory Center Technical Report 1781, Diurnal Phase Variation at 10.2 kHz, by ER Swanson and WR Bradford, 11 August 1971**

First Order Determination of Chart Base

US/Europe Considered

Determination of a typical velocity requires specification of typical conditions. We are especially interested in choosing a velocity suitable for the US coastal confluence and would like a choice compatible with European needs. Splitting the US West and East Coasts (including Gulf) at Eureka, California, and Savannah, Georgia, shows that both coasts can be divided by the geomagnetic dip contour of 64°. This is also the magnetic dip angle of Brest and Paris, France. Hence, a first approximation would be to set the dip angle at 64° and determine velocity.

Velocity also depends on the phase of solar cycle. Considerable variation in sunspot number occurs from year to year and also from cycle to cycle. Approximately 70 may be considered a typical sunspot number.

Velocity under given conditions can be computed from table 2 taken from reference 3:

Table 2. Functional forms, velocity variation coefficients, and confidence limits.

		Velocity Variation Coefficients and Confidence Limits/Day/Night		
Form	Representing	Expected[a] $\times 10^{-4}$	Experimental[b] $\times 10^{-4}$	Assumed $\times 10^{-4}$
ke	excitation (eastbound)	$-4.4^{c,d}$ $8.5^{c,d}$	-3.8 ± 1.3^{c} 13.8 ± 1.5^{c}	-4.8^{c} 13.8^{c}
m (see text)	excitation shift at other bearings	0 8.1^{c}	0.7 ± 0.8^{c} 0.9 ± 1.0^{c}	1.0^{c} 0.9^{c}
$10^{(1-0.325\,D_g)}$	excitation shift for low ground conductivity	4.0^{c} 5.5^{c}	9.6 ± 2.9^{c} 12.5 ± 11.1^{c}	10.0^{c} 5.0^{c}
$(0.9 - 0.573\,\lvert I \rvert)^{1.9}$	dip angle	4.7 -45.4	-20.9 ± 9.6 -53.9 ± 14.0	-6.6 -45.0
$(0.9 - 0.573\,\lvert I \rvert)^{2} \sin\theta$	dip angle and azimuth	-2.9^{e} 101.4^{e}	-22.0 ± 16.9 -17.6 ± 19.1	0.0 -17.6
$(0.9 - 0.573\,\lvert I \rvert)^{2.5} \sin\theta$	dip angle and azimuth	-0.9^{e} -55.0^{e}	28.3 ± 21.6 45.0 ± 26.0	0 45.0
$(0.9 - 0.573\,\lvert I \rvert)^{1.85} \cos 2\theta$	dip angle and azimuth	2.5 46.9	-4.4 ± 5.2 -4.8 ± 6.6	1.0 0.0
$(0.9 - 0.573\,\lvert I \rvert)\,[\sin 3\theta + 0.6 \sin 5\theta]$	dip angle and azimuth	– -7.3	– -3.6 ± 2.2	– -4.0

3. Swanson, ER, "VLF Phase Prediction," Proc VLF-Symposium, Sandefjord, Norway, 27–29 October 1971 (Norwegian Inst of Cosmic Physics Report 7201, January 1972, G Bjontegaard, Ed)

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Table 2. (Continued)

Form	Representing	Velocity Variation Coefficients and Confidence Limits/Day/Night Expected[a] $\times 10^{-4}$	Experimental[b] $\times 10^{-4}$	Assumed $\times 10^{-4}$
$(0.9 - 0.573\,\lvert I \rvert)^{3.5} \cos 4\theta$	dip angle and azimuth	–	–	–
		11.5	22.6 ± 8.9	15.0
$\exp - \left[\frac{(\lvert\varphi\rvert - 1.134)^2}{0.002437} \right]$	auroral zone	?	5.3 ± 2.9	6.0
		?	8.9 ± 4.0	9.4
$\exp - \left[\frac{(\lvert\varphi\rvert - 1.204)^2}{0.002437} \right]$	auroral zone	–	–	–
		?	6.7 ± 6.8	7.2
$2.05\,(\lvert\varphi\rvert - 1.0821)$	polar cap	?	−13.2 ± 5.3	−12.0
		?	13.2 ± 7.3	14.0
1	base velocity (sea water, other parameters zero)	31.1	36.6 ± 1.3	34.3
		4.2	3.2 ± 1.8	3.1
(0.01)(SSN)	sunspot dependence	?	2.1 ± 1.0	2.1
		?	3.3 ± 1.0	3.0

[a] Where values are dependent on profile, $\beta = 0.3\ \mathrm{km}^{-1}$ and $h' = 70$ km assumed for day; $\beta = 0.3\ \mathrm{km}^{-1}$ and $h' = 86$ km assumed for night (conventional notation; see references)

[b] ±95% confidence limits

[c] Centicycles

[d] Expected $k_e = 9.4$ cec day; 10.5 cec night without allowance for excitation region (see text)

[e] Both pairs of coefficients for sin θ should be considered simultaneously

Spatial Computation

Considering only the dip angle, base velocity, and sunspot dependence (table 3):

Table 3. Velocity variations.

Factor	Condition	Parameter Value	Velocity Variation $\times 10^{-4}$ Day	Night
Base	–	1	34.3	3.1
Dip angle	64° dip	0.077	-0.5	-3.5
Sunspot	Number of 70	0.7	1.5	2.1
		Total	35.3	1.7

Comparison of the above with the referenced table shows that several effects have been disregarded. Auroral and polar cap effects are unimportant for the US coastal confluence as the region is usually defined. Excitation effects at transmitters are unimportant as they will simply cause biases which will be similar at both the beacon and user locations. De-excitation will not affect nominal velocity in a region although slight phase shifts might be introduced. Azimuthal variations require comment. Velocity at night is typically lower westbound than eastbound. North and southbound velocities are similar. Thus, as we may consider the signals to an undefined coastal confluence region as arriving more or less omnidirectionally, velocity variations with bearing will not affect east-west lines-of-position; that is, lines-of-position formed by signals from the north or south. However, signals from the west at night will typically have a higher velocity than those from the east. An LOP formed by differencing such a signal from the west against one from the east will thus exhibit a higher than nominal velocity due to both the higher velocity of the signal from the west and the relatively lower velocity of that from the east used in the opposite sense as a reference. This will not enter the problem as a doubling of the effect since the hyperbolic line-of-position already reflects the mutual effect of two signals through nominal spacing at the half-wavelength. However, a substantial effect will be observed. Thus, the preferred charting velocity should be anisotropic. That is, lines-of-position determining longitude should be spaced more closely than those determining latitude. In practice, the velocity during the day is nearly isotropic and hence a significant anisotropy in charting velocity would cause error during the day. A practical compromise is thus choice of a single charting velocity but with some slight regard for the ideal compacting of lines-of-position running north-south. Figure 5 is a polar plot of anomalous anisotropic velocity variation for a dip angle of 64°. Three parts in 10^4 have been added to both the day and night plots so that a circle would be plotted if the velocity variation were isotropic. Apparently, at night increased velocity for propagation to the east is shown as noted earlier. It should be noted that this display reflects the anticipated velocity variation as it would affect charting. The average anomalous velocity variation as a function of bearing is zero as must be the case from the nature of the Fourier representation. However, the variations are such as to displace the centroid. The centroid of figure 5 indicates the preferred night charting relative velocity should be about one part in 10^4 higher than the nominal isotropic velocity. Combining these adjustments with results from table 3 yields updated preferred velocity variations for day and night of 35.3 and 2.7×10^{-4}, respectively.

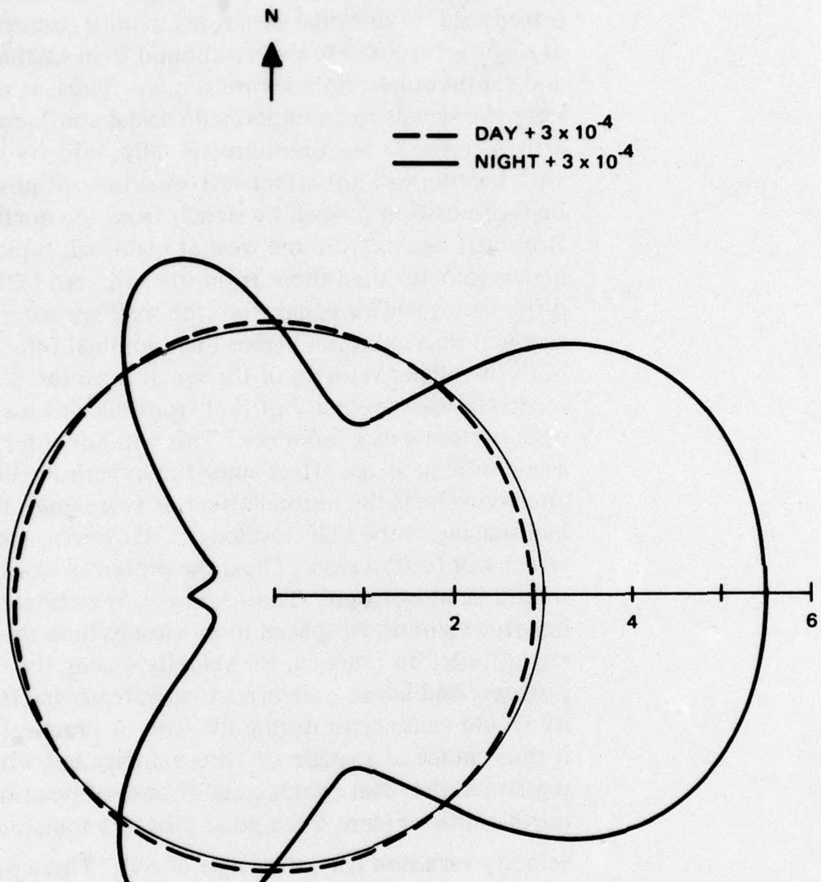

Figure 5. Anisotropic relative velocity variations (× 10^{-4}).

Temporal adjustments

Additional adjustments are needed since the daytime velocity as previously cited is applicable only for paths which are entirely normally illuminated. In practice, no path can be simultaneously normally illuminated at all points and hence further adjustments are required. Typical geographic latitude of the contiguous US coastal confluence is about 37°N; a typical value for Europe is 47°. The zenith angle at 37°N at noon ranges from about 15° in June to 60° in December. The diurnal function is known to be a linear function of the cosine of the solar zenith angle for zenith angles less than 72°. Zenith angles less than 72° occur from approximately 0600 to 1800 local time in June and 0900 to 1500 local time in December at 37°N latitude. Within the region of known applicability, the cosine of the zenith angle thus ranges from arc cos 72° = 0.3 to 0.5 in December and to 0.97 in June. A typical value is near 0.5. As noted in reference 2, p 24, a value for the slope of the diurnal function against the cosine of the zenith angle can be computed as 0.265 for a sunspot number of 70. Thus, more or less typical daytime conditions will be shifted (1–0.5) (0.265) = 13.3% of the maximum diurnal shift toward night conditions. This will not be 13.3% of the variation in velocity due to the influence on the excitation factor in defining the diurnal function. Disregarding this, however, results in an adjustment of daytime relative velocity variation of from 35.3 to 31.0×10^{-4}.

Combining the preceding figures, the best compromise relative velocity variation will be between the day and night velocities: ie, between 31.0 and 2.7×10^{-4}. Some weighting should be used depending on the relative length of day and night. Daytime durations at 37°N have already been noted and average about 9 hours. Ionospheric night at 37°N is from 2000 to 0400 in June and from 1730 to 0630 in December; ie, an average duration of 10-1/2 hours. Weighting the day and night velocities by the respective average durations yields a compromise relative velocity variation of 15.8×10^{-4} for a relative velocity of 1.00158. The corresponding charting constant is c/v = 0.99843.

Preferred US base
c/v = 0.99843

Had the preceding computations been made for Europe at a typical latitude of 47°, the noon zenith angle would have ranged from 25° to 70°. Thus, the cosine of the zenith angle would have reached about 0.6 during the June day but only briefly reached 0.3 in December. Zenith angles greater than 72° would occur from 0600 to 1800 in June and from 1100 to 1300 in December. The average cosine of the zenith angle for the defined daytime period would be 0.375, whence the typical diurnal function would be (1 – 0.375) (0.265) = 0.166.

The nominal daytime velocity variation would thus be 29.9 × 10^{-4}. Weighting according to the typical 7^h day and 10^h night yields a compromise relative velocity variation of 13.9 × 10^{-4}. The corresponding relative velocity is 1.00139 and the chart constant c/v = 0.99861.

Preferred European base
c/v = 0.99861

Second Order Considerations

The foregoing calculations were approached by assuming typical values for parameters and then computing the corresponding effects on velocity. A more precise method would be to determine the range of parameters to be expected in the confluence areas and then compute the corresponding range of effects. Some appreciation for the differences to be expected can be had by noting that 47° corresponds to approximately the northern boundary of the contiguous United States while 37° is near the extreme southern limits of Europe. Thus, we expect the range of values for either Europe or the contiguous United States to differ on the order of ±2 × 10^{-4} from nominal. A more serious question arises if Differential Omega is considered for Alaska or northern Scandinavia. Here a latitude near 60° must be considered. Oslo is at 60°N latitude, which latitude is also midway between Juneau and Anchorage, Alaska. A dip angle of 74° approximates either area. The dip parameter of table 3 can be computed to be 0.031, whence the day and night nominal velocity variations become, respectively, 35.6 and 3.8 × 10^{-4}. Adjustments similar to those in the first order consideration yield corrected day and night values of 35.6 and 4.3 × 10^{-4}, respectively. In June, there is no ionospheric night at 60° north while day with zenith angle less than 72° occurs from 0530 to 1830. There is ionospheric night from mid-July to mid-May reaching a maximum duration of 16 hours in December. However, there is no day with zenith angle less than 72° in December. Such days occur from February to October. Thus, a typical night is 7 hours long while a well illuminated day is 4 hours long. Zenith angles during the day range from 37° to 72°. The average cosine is about 0.43 and the typical diurnal function 0.152. The nominal daytime velocity variation would thus be 30.8 × 10^{-4}. Weighting according to the duration of day and night yields a compromise relative velocity variation of 13.9 × 10^{-4}. The corresponding relative velocity is 1.00139 and hence the chart constant is 0.99861. This is identically the result obtained previously for Europe. The similarity of results reflects a compensation between the dip angle influence raising both the day and night velocities while the increased geographic

Optimum base nearly constant

latitude indicates typical conditions average out to be more "night-like"; that is, require a lower velocity. The compensation is convenient in that the optimum chart velocity is nearly constant throughout the coastal region.

Chart Base Recommendations

Preferred base: $c/v = 0.9985$

From the foregoing, it is apparent that a satisfactory chart base will be $c/v = 0.9985$. Errors due to spatial "dispersion" are shown in figure 6 for 37°N.

COMMENTS

Questions: Compatibility Universality: spatial temporal

The chart base of $c/v = 0.9985$ just derived is clearly a satisfactory choice for Differential Omega in Europe or the United States at a frequency of 10.2 kHz. The questions are: (1) compatibility with existing charts, (2) use in other areas of the world, and (3) chart base selection or reference selec- for other Omega frequencies.

Single base preferred

If practical, it would seem better to keep all Omega charts to the same base. Use of multiple chart bases introduces another variable to the user and another chance of serious error if propagation corrections and chart base are mismatched. Further, conversion from high seas charts to Differential charts when entering a coastal confluence region could cause confusion in operation and lane count. However, a relatively strong case can be made for selecting a chart base which does not seriously degrade Differential Omega. This suggests conversion of all Omega charts and tables to a new chart base. Surprisingly, this is not prohibitively expensive despite what one might at first think. Charts are no longer generated by long, laborious drafting or engraving but rather by high-speed computers, automatic plotters, and overlay techniques. The investments are now primarily in software and organization, and the required revised master tables and charts can be produced automatically by change of a single number in the generating computer programs. Propagation correction tables are revised from time to time in any event so such revision could be coordinated with a change of chart base thus eliminating associated special revision costs. Viewing the revision costs of charts and lattice tables as the cost of a dozen or so automatic airborne receivers helps keep the impact in perspective. In the view of the author, more serious aspects of a change of base concern navigational safety during a changeover. Some confusion undoubtedly would occur and navigational blunders would be likely. The hope would be that the long-term improvements in navigational safety using Differential

Conversion: costs

Safety

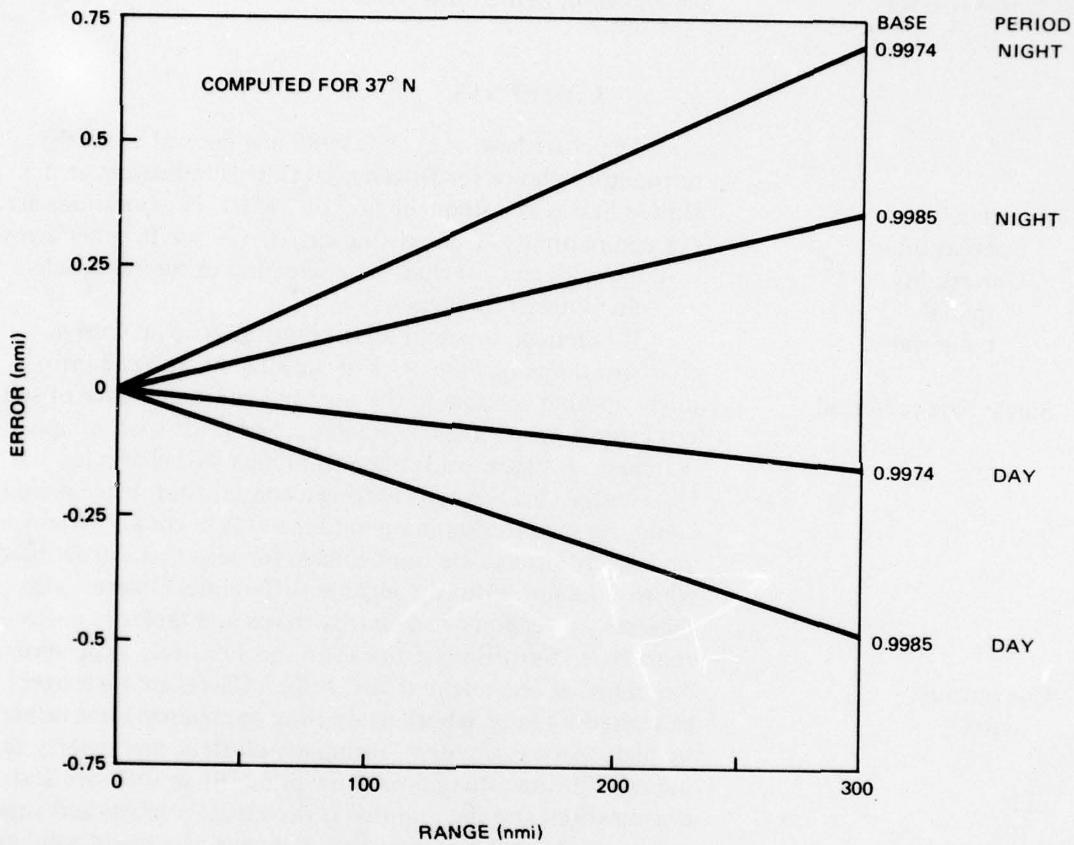

Figure 6. Spatial dispersion error due to chart base.

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Management

Work needed

Differential Omega use of multifrequencies speculative

Omega would offset whatever accidents might occur incidentally to the change. Clearly, the actual planning and management of a base change warrant serious attention.

The chart base derived herein considered only operation in Europe and the United States. Prudence suggests computations be extended to other parts of the world before the recommended base is adopted for international use. Areas of particular interest are the Strait of Malacca and Palk Strait.

Further consideration is warranted on the potential use of Omega frequencies other than 10.2 kHz for Differential Omega. Little work has been done on Differential Omega other than at 10.2 kHz. However, Differential Omega telemetry has been proposed for other Omega frequencies as well.[4] Further, the current "Provisional Preliminary Draft" of Operational Standards for Differential Omega by the Differential Omega Working Group of the Inter-Governmental Marine Consultative Organization (IMCO) suggests that the format should allow " . . . benefit to the utmost from all available Omega information." Multifrequency Differential Omega use may evolve to follow present trends with standard Omega in which manual operation is restricted almost entirely to 10.2 kHz except for infrequent lane resolutions while automatic receivers may use the full format. In this case, adoption of special "bases" solely to reference differential corrections for frequencies other than 10.2 kHz can be recommended. If, however, significant manual usage of 13.6 kHz were to evolve, then considerations of chart base should be quite different.

CONCLUSIONS AND RECOMMENDATIONS

A chart base of $c/v = 0.9985$ is recommended for Differential Omega at a frequency of 10.2 kHz in Europe and the United States.

Serious consideration of a change of base of the entire Omega system is warranted.

4. Swanson, ER, Adrian, DJ, and Levine, PH, "Differential Omega Navigation for the US Coastal Confluence Region," NAVIGATION 21, 3, Fall 1974, p 264–271

REFERENCES

1. Navy Electronics Laboratory Report 1305, Omega Lane Resolution, by ER Swanson, 5 August 1965
2. Naval Electronics Laboratory Center Technical Report 1781, Diurnal Phase Variation at 10.2 kHz, by ER Swanson and WR Bradford, 11 August 1971
3. Swanson, ER, "VLF Phase Prediction," Proc VLF-Symposium, Sandefjord, Norway, 27–29 October 1971 (Norwegian Inst of Cosmic Physics Report 7201, January 1972, G Bjontegaard, Ed)
4. Swanson, ER, Adrian, DJ, and Levine, PH, "Differential Omega Navigation for the US Coastal Confluence Region," NAVIGATION 21, 3, Fall 1974, p 264–271

ADDENDUM

7 April 1978

As noted in the administrative foreword, a draft of this report was discussed at the second meeting of the Intergovernmental Marine Consultative Organization (IMCO) Intersessional Working Group (ISWG) on Differential Omega (DO) in Paris 3–7 April. At that time Monsieur G Nard of the French delegation said he had thought at length on the charting problem posed by Differential Omega and drew attention to the possibility of employing a more suitable base with charts for Differential Omega but offsetting the grid so that Lines-of-Position would be identical at the Differential Omega beacon monitor. This idea had crossed the author's mind but had been rather instantly discarded for a number of formal reasons. Local charts would then depend on precise monitor siting and would require change if a monitor were moved. If a beacon failed and a back-up beacon were being used in its extended service area, the grid would no longer be correct. Automatic receivers would extrapolate on the Global base unless given the monitor location. Convectional Omega Navigators would experience an error if using the special Differential Omega coastal charts with standard correction procedures. Positions obtained using differential corrections received from beacons to both sides of a navigator could not easily be averaged. While true, the impact of these formal objections may not be sufficiently great that this approach should not be considered. Monsieur Nard personally favors the foregoing if the entire chart base of Omega is not changed. Further work is warranted regarding aspects of this particular option for Differential Omega charting.

The substance of the work in the body of the report is, of course, not fundamentally affected by this particular option.